Single-Phase Battery-Buffered Smart Load Controller

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***Abstract*- This paper presents the design and experiment of a single-phase battery-buffered smart-load (BBSL) controller and its test bench. The motivation for this work is to investigate the design and operation of a BBSL system that will be beneficial for both power grid operation and customers. As a functional experimental system, the developed single-phase BBSL works at a low-voltage level (24 Vac and 48 Vdc) with a fixed-point microcontroller and a LabVIEW-supported test bench. The issues and experimental results include firmware evaluation, line frequency detection with Second-Order-General-Integral Phase-Locked Loop and battery control strategy for primary frequency regulation.**

***Keywords*- battery, smart load, controller, power grid, line frequency**

I. INTRODUCTION

Load-side participation in power system control and operation is becoming more and more important in the power grid operations and research [1]-[3]. In traditional power grids, the control and operation is performed mainly from centralized generation stations and control centers of interconnected areas. Although total effect of loads connected to a grid is almost equal to that of all generators in the same grid, all these loads are generally treated as "passive" components in the grid control. In the model of a power system, loads are generally modeled as stable power flow with switching-on or –off functions. This situation will change because of new challenges to traditional power grids. These challenges include: 1) relative slow development of existing power grids and fast increase of both total electricity consumption and peak loads in recent and coming years; 2) large scale integration of renewable energy with intermittent properties and inverter-based power generation [1]; and 3) increasing load disturbances because of widely synchronizing events [5] or large area natural disasters. In the official definition of a smart grid a decade ago, integration of 'smart' appliances and consumer devices is an important feature to be achieved [8].

Dynamic demand control (DDC) and demand response (DR) are two proposed classes of load-side participation in power system control and operation. DDC proposed in [1] is to apply the traditional load-frequency control strategies [6] of synchronous generators to the demand side. It includes both primary frequency regulation (PFR) and secondary frequency regulation (SFR), in which the deviation of the line frequency from the rated value is detected and used to control load power consumption of appliances. The loads discussed in [1] are the appliances not critical in time-of-use (ToU) within reasonably narrow time periods, such as refrigerators, air conditioners, and water heaters. In this method, load-side dynamic power control will be supplement to the automatic generation control (AGC) so that the system dynamic performance and stability are improved. DDC will help to stabilize a power grid with significant renewable energy penetration.

Based on the description of the Department of Energy website [7], DR is an electricity tariff or program established to motivate changes in electric use by end-use customers, designed to induce lower electricity use typically at times of high market prices or when grid reliability is jeopardized. DR may help to reduce peak load power consumption by encouraging customers to shift their energy demands from "peak load" time. It will also help to increase renewable energy penetration by changing customers' energy behavior.

Although DR is becoming more and more popular in recent years, the effects of DR programs is fairly limited. As discussed in [9], DR requires considerable active efforts of consumers, for example, to pay attention to the energy information, to decide on appropriate actions, and even to add local alternative generation. DDC has not been widely adopted by customers yet. Currently, DDC is proposed only for special loads based on a random control strategy. It may result in some unexpected effect of customers' power consumption. As proposed in [1], the DDC control capability is only effective for under-frequency regulation. Additionally, it requires installation of DDC controllers at the customers' appliances, which may also hamper customers' acceptance.

A reasonable battery storage installed at load-side as an energy buffer will separate the load power consumption from the grid and reduce the impact of DDC and DR on customers. Batteries are a popular type of energy storage. Battery storage systems (BSS) have been widely used in electrical vehicles (EV), wind and solar power generation, substations, and various uninterrupted power supply (UPS). Different from traditional grid-level energy storage, such as pumped hydroelectric energy storage and compressed-air energy storage, BSS are scalable, mobile, and exchangeable. These characteristics make batteries more suitable for the load-side applications than other energy storage systems. However, up to now, BSS is often a big investment for many customers. The life-time of a BSS is another concern compared to more than 30 years life time of traditional grid-level equipment.

Batteries have been widely used on load-side applications, such as in laptop computers, UPS, and so on. Recently, behind meter battery storage is also commercially available. These applications are mainly for special purposes, for example device mobility or data protection of information systems. In practice, the batteries in such applications are often not fully used because they are not always necessary for system operation. Most people use laptop computers with power plug-in, and an UPS only works when a blackout occurs. The existing applications tell us that customers are willing to invest for attractive features of power supply with batteries though batteries are quite expensive. It is possible for customers to accept batteries as an energy buffer between a power grid and their appliances as long as they believe that the new features are important or beneficial. BBSL technology was proposed in this work with the goal of combining the functions for the load-side participation of power system control and the beneficial features for customers in new load-side application designs. The expected power rating of a BBSL is mainly in the level appliances, from a laptop computer to power supply of a residential house, i.e., from 100 VA to 20 kVA.

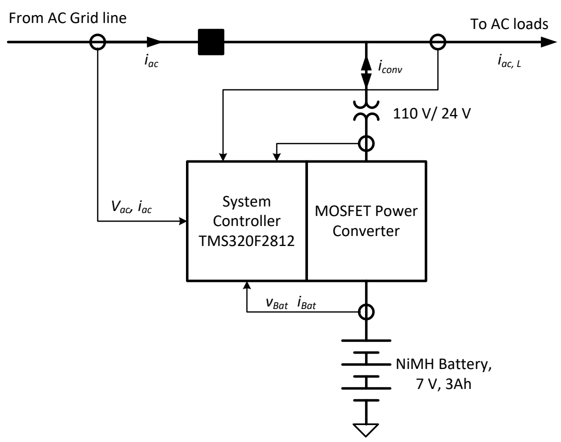
The following sections of this paper present the design of a low-voltage functional BBSL controller and BBSL test bench; the high-precision line frequency detection based on Second-Order-General-Integral Phase-Locked Loop (SOGI-PLL); and a control strategy of BBSL for battery with PFR. We also present and discuss the evaluation of firmware, experimental results of line frequency detection, and the experimental result of PFR with state of charge (SoC) control. The contents are organized in the following sections (1) BBSL controller, (2) design of single-phase BBSL controller, (3) firmware description, (4) LabVIEW-based BBSL test bench, (5) experimental results, and (6) conclusions.

II. BBSL CONTROLLER

A BBSL controller is designed for a conventional load to implement smart-load features. Its fundamental function is to optimally control the grid power flow to a load by evaluating the states of power grid operation, the load power consumption, and battery storage as shown in Fig. 1.

Equipped with battery storage, a BBSL can be designed to implement DDC and DR automatically and, at the same time, to meet the customers' additional requirements for power supply. The capability is mainly restricted by the energy/power capacity of the installed battery. As an important part of BBSL control, the PFR function is discussed in the following.

Fig. 1. BBSL functional scheme.



A. BBSL Primary Frequency Regulation

PFR is a widely used control strategy of governors in synchronous generator systems. A governor automatically controls power generation based on line frequency deviation as:

$$\Delta P_g = \Delta P_{set} - \frac{\Delta f}{R} \quad (1)$$

where ΔP_g and ΔP_{set} are the change of power generation and setting, respectively. Δf is the line frequency deviation from the rating value. R is the regulation constant [6].

Similar to a generator, PFR can also be applied to a BBSL as,

$$P_{grid} = P_{load} + \frac{\Delta f}{R} \quad (2)$$

where P_{grid} and P_{load} are the grid power delivered to BBSL and the load power consumption, respectively. The difference between the grid power and load power charges or discharges the battery storage. As a load, one restriction is $P_{grid} \geq 0$, or the grid power to a BBSL unidirectional.

There are good reasons to design PFR function so that it will not affect the SoC of the battery storage significantly. PFR is a dynamic compensation of a power grid. The energy storage is used to implement both underfrequency and overfrequency while the SoC is kept around a setting value, for example 80%. The reserved energy stored in the battery could be used for DR application or UPS function when it is required. By considering this fact, the grid power control in (2) can be modified as:

$$\Delta P_g = \Delta P_{set} + K_{SoC}\Delta SoC - \frac{\Delta f}{R} \quad (3)$$

where K_{SoC} and ΔSoC are the control gain and deviation of SoC from its setting value of 80%.

All quantities in (1), (2), and (3) are in per unit. The regulation constant is often chosen equal to 0.04. The practical line frequency deviation in normal system operation is generally not more than 0.2 Hz, or 3.3×10^{-3} *pu* for the base line frequency of 60 Hz. The change of the grid power because of PFR should not be more than 0.1 *pu*. Therefore, the base power of the system can be 10 times of the rated power of the battery. For a NiMH battery of 20 watts, it can support load-side PFR at the base power of 200 Watts.

B. Line Frequency Detection

The detection of line frequency is necessary for BBSL load-side PFR. Based on NERC Reliability Standard PRC-024-1, the deviation of line frequency is in the range of ±0.5 Hz for steady state and ±2.2 Hz for dynamic state. However, the frequency deviation is usually around 20 mHz to 40 mHz. The precision of 1 mHz or 0.045% (based on dynamic range of line frequency deviation of 2.2 Hz.) should be reasonable for BBSL applications. It is significant to develop a method to detect the line frequency at such a high precision that is effective in the noisy load environment and easy to be implemented in BBSL controllers at a low-cost. In this work, SOGI-PLL was investigated theoretically and experimentally for the frequency detection. In single-phase inverters, SOGI-PLL is widely used for line voltage synchronization [4].

In a BBSL controller, SOGI-PLL was designed for both phase synchronization and the frequency detection. Because PLL is a closed-loop control system, there is no special restriction on resolution for the frequency detection, theoretically. However, the controller may introduce significant control noise. It requires well-designed filters and the reasonable selection of a sampling rate to detect the frequency for the required precision. In this work the frequency sampling rate is 10 samples per second while the PLL control frequency is 10 kHz. Figure 2 shows the functional block diagram of the SOGI-PLL-based phase synchronization and frequency detection. The detected frequency from SOGI-PLL f_{PLL} is in per-unit with the base value of 60 Hz. The method can easily be applied in a 32-bit fixed-point microcontroller with 12-bit AD converter.

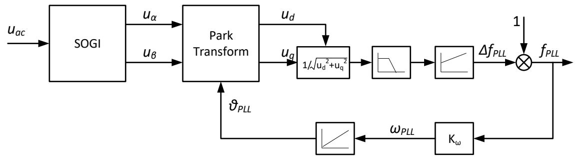


Fig. 2. SOGI-PLL based frequency detection.

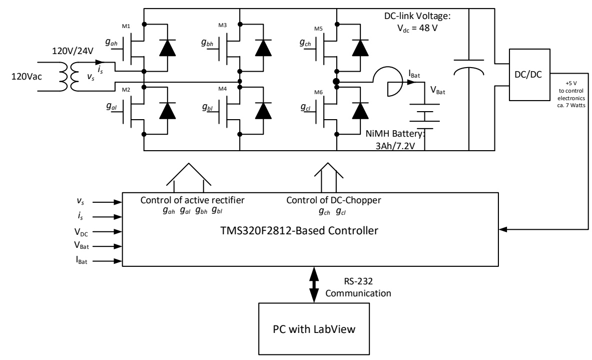
III. Design of Single-Phase BBSL Controller

The goals in designing a BBSL controller test system are 1) to investigate the performance and model of various batteries, 2) to investigate the BBSL control strategies, 3) to evaluate the firmware of a microcontroller and 4) to provide a test bench in the research laboratory. The single-phase BBSL controller at a low-voltage level (24 Vac and 48 Vdc) was designed and developed for safety and economics.

The experimental system shown in Fig. 1 consists of a 200 W, 110 V/24 V transformer, single-phase full-bridge converter, a buck/boost converter, a 7 V/3 Ah NiMH battery, and a digital controller based on TMS320F2812 from Texas Instruments, Inc.

A MOSFET three-phase full bridge inverter developed in the laboratory was used for the single-phase full-bridge inverter and the buck-burst converter as depicted in Fig. 3. Based on the widely used three-phase full-bridge inverter, the design has significant economic advantages for future manufacturing. The control of the single-phase inverter include a SOGI-PLL and a modified proportional-resonant (PR) controller [4]. The SOGI-PLL is designed to evaluate grid voltage phasor and frequency. The evaluated data are fed into the PR controller for the current control of the single-phase inverter. In addition these data are also used in the BBSL controller for the PFR and the early detection of an outage.

Fig. 3. Power circuit of the single-phase BBSL controller.



IV. Firmware Description

TMS320F2812 is a fixed-point 32-bit micro-controller. Compared to more advanced 32-bit microcontrollers with floating-point processors, a fixed-point microcontroller is more suitable for the practical design of commercial products with the advantages of low cost and low energy consumption.

The control of active rectifier including SOGI-PLL and PR controller requires much high precision computation. Without a floating-point processor, the functions of IQmath library provided by TI are widely used in the firmware. The main control function operates at 10 kHz, which includes all real-time signal sampling, digital signal processing and control functions. The important control functions for the single-phase active rectifier are SOGI-PLL, PR controller with voltage feedforward compensation, notch filter for detection of DC-link voltage, and conventional proportional-integral (PI) controller. The microcontroller works at the system clock of 150 MHz. The execution time consumption of the main functions is listed in Table I.

The main control function for the real-time control takes 37.2 µs, or 37.2% computation capacity of the microcontroller. In addition, there are functions such as RS-232 data communication, system initialization and analog signal calibration that are not time critical.

TABLE I.
TIME CONSUMPTION OF MAIN FIRMWARE FUNCTIONS

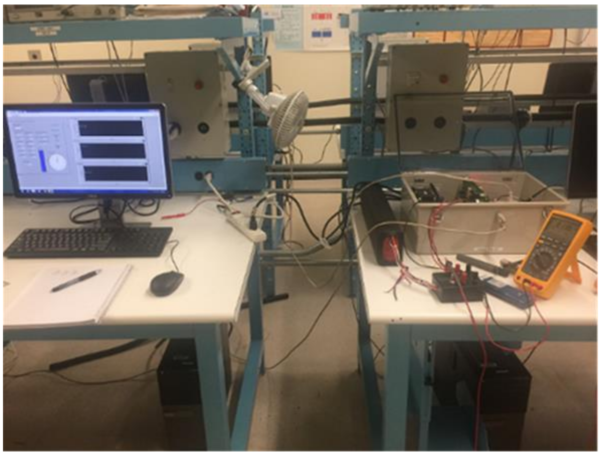
Function	Time (µs)
Main control function	37.2
SOGI-PLL	6.24
Modified PR controller	13.6
PI controller	0.872
Notch filter	0.936

V. LABVIEW-BASED BBSL TEST BENCH

The LabVIEW program allows a desktop computer to realize human-machine interface and system-level control. Through an RS-232 port, the LabVIEW program accesses the microcontroller data for further data processing, graphical display, and data storage, and sends control commands and data back to the microcontroller. The LabVIEW program operates at a much lower control frequency compared to the main function in the microcontroller, such as 1 Hz, which is reasonable for a desktop without a real-time operating system. The obvious advantage with the LabVIEW program is its convenience for development and modification as well as capabilities to use the much more sophisticated functions in network communication and file management provided by a desktop computer.

The LabVIEW program also provides remote-access capability for the test bench. The user can operate and monitor the experiments remotely from a desktop computer. This feature is very helpful for the experiments with battery and BBSL control strategy study because many experiments require 24 hours a day operation.

(a)



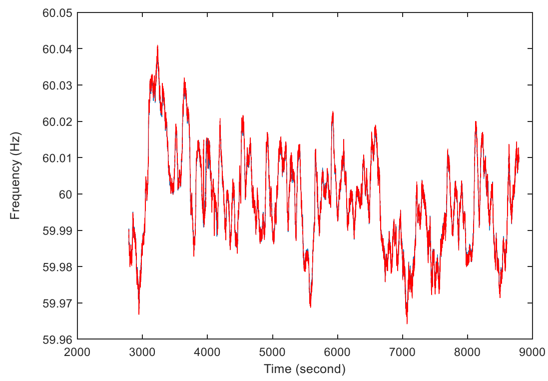
(b)

Fig. 4. (a) BBSL system (b) and the BBSL test bench.

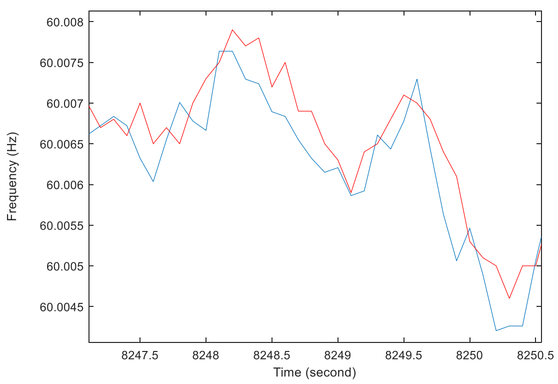
VI. EXPERIMENTAL RESULTS

Many system experiments have been performed to study the model of NiMH batteries, to confirm the effectiveness of line-frequency detection, and to investigate BBSL strategies such as PFR with battery SoC control. The experimental results of frequency detection and PFR with SoC control are discussed here. The BBSL system is shown in Fig. 4(a) and BBSL test bench in Fig. 4(b). The small fan is the AC load of about 16 watts. The battery used in the experiments is a 7.2 V/3 Ah NiMH battery.

To evaluate the precision of the line frequency detected with SOGI-PLL, FDR frequency data provided by PowerIT lab, University of Tennessee, Knoxville, were requested and used as a reference. FDR frequency data were detected with a high precision grid analyzer [10]. The detected frequency with a SOGI-PLL were compared with the FDR frequency data remotely recorded at the same location (Little Rock, AR72212) and within the same time duration (from 3:47:18 p.m. to 5:27:18 p.m. Central Time on Dec. 30, 2017). The comparison is shown in Fig. 5(a). The blue line is the frequency measured by BBSL controller and the red line the FDR frequency data provided. To take a good look at the



(a)



(b)

difference between the two measured frequencies shown in Fig. 5(a), a small section of 3.5 s is magnified and shown in Fig. 5(b). The peak errors between the two measured frequencies are about 0.5 mHz.

Fig. 5. Comparison between BBSL controller frequency evaluation (blue) and FDR frequency data (red).

Fig. 6 shows the experimental results of a primary frequency regulation with battery SoC control realized with the BBSLC test bench. The test began at 1:14:35 p.m., Sept. 4, 2017 and continued for about 2.5 hours. At the beginning of the experiment, the battery is fully charged (100% SoC). In the PFR experiment, the battery SoC is controlled equal to 80% in normal operation. The waveforms include the detected line frequency Freq., the grid power Pgrid, the load power Pload, the battery power regulation Preg, and battery SoC. The battery power is regulated by BBSL controller. When it is positive, it charges the battery. When it is negative, the battery supplies part of the load power.

Because the battery SoC began with 100%, the SoC controller generated a power offset to discharge the battery until the SoC reached about 80%.

In PFR, BBSL controller regulated the battery power based on the detected line frequency deviation with the regulation constant $R = 0.04$ per unit with the base power of 200 Watts. The experimental waveforms show that the BBSL

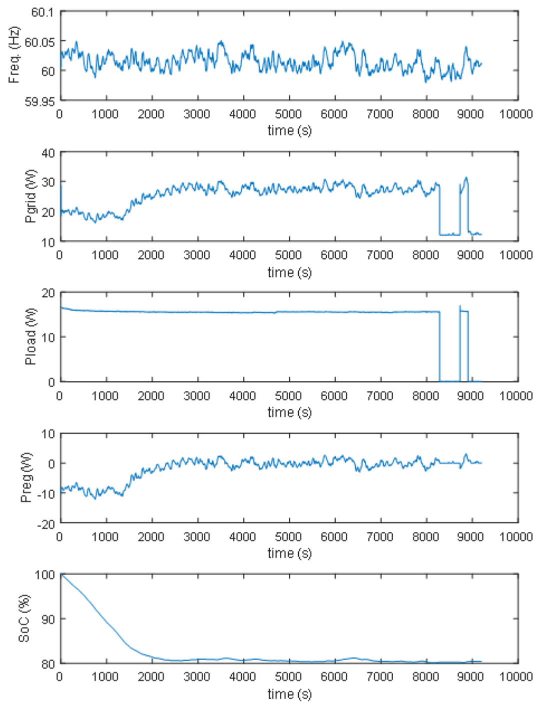


Fig. 6. BBSL waveforms with PFR and SoC control.

PFR was effective until the load was switched off.

In the experiment, the sum of the load power and the battery power was controlled to be not less than zero, which means the load with the battery will never feedback the energy to the power grid. In the experiment, the grid power shown in Fig. 6 included the BBSL controller power consumption of about 11 watts. It was not included in the load power shown in Fig. 6.

VII. Conclusions

Battery-buffered smart loads are proposed in this work. Equipped with a battery storage system, a BBSL is able to implement DDC and DR automatically, which will help the load-side participation of power system control and operation. With battery energy storage, a BBSL will also be designed to realize various customer attractive functions, such as UPS, which may overcome the barriers to customer investment.

A single-phase BBSL controller was designed and the BBSL test bench developed for the experimental study of BBSL operation. The operation of a BBSL with PFR and battery SoC control was investigated. By setting a reasonable gain for SoC control, the battery SoC can be controlled around a desired value while the BBSL operates in PFR. This work also confirmed that the SOGI-PLL can be applied for line frequency detection at a high precision of 1 mHz. The line frequency detected with the test BBSL controller matched the FDR frequency data quite well.

ACKNOWLEDGEMENTS

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